

1 **NON-CONTACT MOBILE CHARGE MEASUREMENT WITH LEAKAGE**
2 **BAND-BENDING AND DIPOLE CORRECTION**

3 **BACKGROUND OF THE INVENTION**

4 The present invention relates to the field of semiconductor
5 wafer testing and, more particularly, to a non-contact method for
6 testing such wafers.

7 In the semiconductor industry, the behavior of FET and
8 bipolar devices used to fabricate integrated circuits are very
9 sensitive to induced charges on the silicon wafers. These
10 induced charges can result from static charging of insulator
11 surfaces, poorly formed oxide/silicon interfaces and excessive
12 ionic contamination within the insulator bulk.

13 The most prevalent source of ionic contamination is sodium.
14 Other less prevalent sources are potassium and lithium. Some
15 sources of sodium can be contaminated quartz ware, incompletely
16 removed photoresist and inadvertent human contact. The common
17 approach to test for sodium contamination is the use of various
18 MOS monitoring techniques. Bias temperature stressing methods
19 are used to electrically quantify the concentration of sodium in
20 insulator layers (usually thermal oxides). The sodium is forced
21 to move down and up in the oxide layer (push-down and pull-up)
22 and then the sodium is either detected as: (1) a change in net
23 charge imaged on the silicon surface (before and after sodium
24 movement) or (2) a change in integrated ionic current (before and
25 after sodium movement) or (3) as a momentary ionic current
26 (during sodium movement).

27 Although widely accepted, the MOS methods have increasingly
28 unacceptable high cost and excessive time associated with the MOS
29 sample preparation. For monitoring thick oxides, the sample
30 preparation time for aluminum MOS electrodes can be 1-2 days and
31 for thin oxides, the cost and time for fabricating polysilicon
32 electrodes is even worse. Furthermore, the fabrication process
33 for these MOS electrodes can become a source for sodium or other

1 measurement complications.

2 U.S. Patent No. 5,498,974, which is incorporated herein by
3 reference, teaches a method and apparatus for measuring mobile
4 charge in an oxide layer on semiconductor wafers using corona
5 charge.

6 A corona gun is used to deposit a measured quantity of
7 charge on the oxide surface and then a Kelvin probe is used to
8 measure the potential of the oxide surface. The wafer is
9 alternately situated under the corona gun and then under the
10 Kelvin probe until a series of values of potentials are reached.

11 The mobile charge measurement is based on the difference
12 between the actual charge required to achieve a desired potential
13 and the theoretical amount of charge required for zero mobile
14 charges.

15 SUMMARY OF THE INVENTION

16 A method for measuring mobile charge in a dielectric layer
17 on a substrate includes applying at least one first polarity
18 corona bias temperature stress cycle to the layer, applying
19 successive second polarity corona bias temperature stress cycles
20 to the layer and measuring a corresponding voltage drop until the
21 voltage drops approach a terminal value, and determining the
22 mobile charge according to the voltage drops.

23 The invention uses a non-contact approach to solve the MOS
24 sample problems. No sample preparation is required and the
25 sensitivity can be made to approach that of the MOS triangular
26 voltage sweep method.

27 BRIEF DESCRIPTION OF THE DRAWINGS

28 FIG. 1 is a combination block and schematic diagram of an
29 apparatus for practicing the invention.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

2 Referring to FIG. 1, a contactless corona-oxide-
3 semiconductor mobile ionic charge measurement apparatus,
4 generally referred to by numeral 10, is shown. The apparatus 10
5 includes, in part, a temperature controllable wafer chuck 12, for
6 heating and cooling a semiconductor wafer 14 to be tested. The
7 wafer 14 includes a semiconductor substrate 16 (e.g., doped
8 silicon) having a dielectric layer 18 (e.g., silicon dioxide)
9 thereon. The surface of the wafer 14 also has an air/dielectric
10 boundary surface 20 and a dielectric/substrate boundary surface
11 22. A measurement region 24 and a measurement region 25 depict
12 respective regions of the dielectric layer 18 selected for
13 testing.

14 A calibrated corona discharge source or corona gun 26 is
15 provided for depositing corona charge on the surface 20 of the
16 dielectric layer 18. An electrostatic measurement device or
17 Kelvin probe 28 enables a surface voltage potential of the wafer
18 14 to be measured. A surface photovoltage measurement (SPV) tool
19 70 enables the surface photovoltage of the wafer 14 to be
20 measured. A high speed linear translational positioner 30
21 provides a desired positioning of the corona gun 26, the Kelvin
22 probe 28, and the SPV tool 70 above the dielectric layer 18 of
23 the wafer 14. The corona gun 26, the Kelvin probe 28, and the
24 SPV tool are suitably attached to a movable carriage 32 of the
25 positioner 30. The apparatus 10 also includes a controller 34
26 for device operability.

27 The wafer chuck 12 may be any suitable temperature
28 controllable wafer chuck, such as is commercially available from
29 Temptronic Corporation of Newton, MA. The wafer chuck 12
30 preferably has good electrical isolation between the chuck
31 heating element and the top surface of the chuck to minimize any
32 introduction of noise into measurements made by the apparatus 10.
33 The wafer chuck 12 is connected to the controller 34 via a signal

1 line 13 for maintaining a desired temperature on the surface of
2 the chuck 12 for heating the wafer 14. The wafer 14 is ohmically
3 connected to the surface of the wafer chuck 12 by a suitable
4 means, such as a tungsten carbide needle.

5 The corona gun 26 includes a corona charge depositing needle
6 36 (e.g., one or more tungsten carbide needles) which is
7 connected to a high voltage supply 38. The corona gun 26 also
8 includes an electrode housing 40, which in conjunction with the
9 needle 36, provides a focusing of the corona discharge. To
10 ensure charge uniformity, the needle 36 is disposed a distance
11 above the surface of the dielectric layer 18 to ensure that
12 fringing effects and other causes of charge deposition non-
13 uniformity are minimized. Typically, such a distance is on the
14 order of several centimeters above the surface 20. In addition,
15 an aperture mask 42, having an aperture diameter on the order of
16 two centimeters, may be attached to the housing 40. The aperture
17 mask 42 is deposited over the surface of the dielectric layer 18
18 with spacing on the order of 10 mils to provide good charging
19 definition and uniformity. In addition, an unshown conductive
20 screen may be interposed between the corona gun 26 and the wafer
21 14 to further enhance uniformity of charge deposition. The high
22 voltage supply 38 provides a desired voltage output in a range
23 from minus 10 kv to positive 10 kv for example. The high voltage
24 supply is suitably connected to the controller 26 via an
25 appropriate signal line 39, for a desired feedback control of the
26 high voltage supply 38 during an operation of the apparatus 10.

27 The SPV tool 70 measures the voltage difference between the
28 top surface 20 of the dielectric layer 18 and the bulk silicon
29 substrate 16 of the wafer 14 that is produced in response to
30 light. SPV tools are well-known in the art and only briefly
31 discussed herein. For instance, a typical SPV tool includes a
32 varying intensity light source that is directable onto the test
33 surface. This light is typically directed through a transparent
34 electrode located within a few mils of the test surface. Any
35 surface voltage produced by the varying light is capacitively

1 sensed by the transparent electrode. In the present invention,
2 the varying light source is of high intensity, for example, a
3 xenon flash tube.

4 The Kelvin probe 28 includes a non-contact means for
5 measuring the voltage difference between the top surface 20 of
6 the dielectric layer 18 and the bulk silicon substrate 16 of the
7 wafer 14. Kelvin probe apparatus are well-known in the art and
8 only briefly discussed herein. For instance, a typical Kelvin
9 probe apparatus includes a capacitive pick-up plate 44 connected
10 to a vibrating apparatus 46. The pick-up plate 44 has a diameter
11 on the order of 0.6 cm for example. The Kelvin probe 28 is
12 suitably positioned above the top surface 20 of the dielectric
13 layer 18 by the positioner 30, such that, the pick-up plate 44
14 is capacitively coupled to the wafer 14 across an approximate 5
15 mil air gap. The vibration of the pick-up plate 44 relative to
16 the surface 20 induces a time varying charge on the surface of
17 the pick-up plate 44, at the vibration frequency of the vibrating
18 apparatus 46. The resultant time varying current at the
19 vibration frequency is proportional to the potential difference
20 between the pick-up plate 44 and the dielectric surface 20. The
21 time varying charge on the pick-up plate 44 is coupled to a high
22 input impedance MOSFET and subsequently to a Kelvin control 48,
23 resulting in a voltage V_s which approximates the surface voltage
24 potential on the surface 20, relative to the underlying substrate
25 16. A signal line 49 connects the controller 34 Kelvin control
26 48, as appropriate, for control of the Kelvin control 48 and for
27 the obtaining of surface voltage potential information during an
28 operation of the apparatus 10. It should be noted that any other
29 suitable non-contact electrostatic voltmeter, such as, available
30 from Trek Corporation of Medina, NY, may be substituted for the
31 Kelvin probe 28.

32 The positioner 30 provides a desired positioning of the
33 corona gun 26, the SPV tool 70, and the Kelvin probe 28 above the
34 dielectric layer 18 of the wafer 14. The positioner 30 includes
35 a movable carriage 32 and a position actuator 50 for controlled

1 translational movement of the carriage 32 to a desired position
2 or positions along a track 52 of the positioner 30. The
3 positioner 30 may include any suitable controllable positioning
4 means or translational stage. The actuator 50 and the track 52
5 may include, for example, a suitable stepper motor and worm gear,
6 respectively. Alternatively, the actuator 50 and the track 52
7 may likewise include a suitable arrangement of pneumatic
8 actuators and guide rails. The positioner 30 is suitable
9 attached to a mechanical ground 54. The positioner 30 also may
10 provide, for example, three dimensional translation of the corona
11 gun 26, the Kelvin probe 28, and the SPV tool 70.

12 The corona gun 26, the SPV tool 70, and the Kelvin probe 28
13 are suitably attached to a the carriage 32 by a suitable spaced
14 amount as shown in FIG. 1. During an operation of the apparatus
15 10, the corona gun 10, the SPV tool 70, and the Kelvin probe 28
16 are selectively positioned above the measurement region 24 (or
17 the region 25) of the dielectric layer 18, the direction of such
18 positioning as indicated by the arrow 55 for the case of single
19 dimensional translation. During a corona discharge step, the
20 corona gun 26 is positioned above, and approximately centered
21 with respect to, the measurement region 24 (or the region 25).
22 During a surface voltage potential measurement, the Kelvin probe
23 28 is positioned above, and approximately centered with respect
24 to, the measurement region 24 (or the region 25). During a SPV
25 measurement, the SPV tool 70 is positioned above, and
26 approximately centered with respect to, the measurement region
27 24. The actuator 50 is suitably connected to the controller 26
28 via an appropriate signal line 51, for a desired positioning of
29 the corona gun 26, the SPV tool 70, and the Kelvin probe 28
30 during an operation of the apparatus 10.

31 Upon exposure of the dielectric layer 18 to a corona
32 discharge from the corona gun 26, a corona current I_c from the
33 corona gun 26 flows into the wafer 14 and then the chuck 12.
34 This current is converted to a voltage by an operational
35 amplifier 56 and then integrated by an operational amplifier 58

1 to generate a voltage proportional to the coulombs of corona
2 charge Q_c deposited on the surface 20. The current I_c is fed
3 back to the controller 34 via a signal line 57, which in turn,
4 provides appropriate control of the high voltage supply 38 and
5 thus the voltage to the corona discharge needle 36, in order to
6 form a constant corona current servo. In addition, the output
7 of the integrating amplifier 58 is connected to the controller
8 34 via the signal line 59 for providing deposited corona charge
9 Q_c information to the controller 34 for use during an operation
10 of the apparatus 10.

11 The controller 34 provides a means for controlling the chuck
12 12, the corona gun 26, the SPV tool 70, the Kelvin probe 28, and
13 the positioner 30 in a controlled manner. The controller 34 may
14 include, for example, a computer and associated interface
15 circuitry, a suitable programmable control device, or the like,
16 for providing desired control, data acquisition, and data
17 manipulation functions. Preferably, the controller 34 includes
18 a computer and associated interface circuitry, computers and
19 associated interface circuitry being well known in the art and
20 only briefly discussed herein, the computer further being
21 programmed by known techniques for performing desired functions
22 as described herein. During a testing operation, the controller
23 34 generates a measurement of an amount of mobile ionic species
24 in a dielectric layer of a wafer under test. To this end, the
25 controller 34 may provide an output signal Q_{Mobile} on a signal line
26 35, wherein Q_{Mobile} is representative of the amount of mobile ionic
27 species in the dielectric layer of the wafer under test. The
28 controller 34 may also include an unshown display device for
29 presenting an analogous indication of an amount of mobile ionic
30 species in the dielectric layer of the wafer under test, such as,
31 by a suitable plot or graph. In addition, an input device 60,
32 such as a keyboard, is connected to the controller 34 for entry
33 of information as necessary for a particular testing operation.

34 A corona calibration electrode 64 and current meter 66 are
35 provided for calibrating a corona density deposited by the corona

1 gun 26. The electrode 64 is of known dimension, such as, having
2 a top surface of a diameter on the order of one centimeter.
3 Furthermore, the top surface of the electrode 64 is positioned
4 in a substantially similar plane as the top surface 20 of the
5 dielectric layer 18. The current meter 66 is connected to the
6 electrode 64. A signal line 67 connects the controller 34 with
7 the current meter 66, as appropriate for control of the current
8 meter 66 and for the obtaining of corona current information
9 during a calibration of the corona gun 26, and further during an
10 operation of the apparatus 10. During a calibration of the
11 corona gun 26, the corona gun 26 is suitably positioned above the
12 electrode 64 via the positioner 30. Under control of the
13 controller 34, the corona gun 26 deposits charge on the electrode
14 64 to establish the corona charge density (e.g., coulombs/cm²) of
15 the corona gun 26.

16 The apparatus 10 is used to measure the mobile ionic charge
17 Q_{Mobile} in the dielectric layer of a wafer under test. This is
18 accomplished by subjecting the wafer 14 to a series of corona
19 bias temperature stress cycles and making various measurements
20 during the process.

21 The wafer 14 is placed on the chuck 12 with the dielectric
22 layer 18 of interest facing away from the chuck 12. It is
23 possible that the wafer will also have an unshown dielectric
24 layer between the chuck 12 and the substrate 16. An ohmic
25 contact is made between the substrate 16 and the chuck 12 with,
26 for example, a sharp tungsten carbide needle 68. The needle 68
27 is typically used to scratch through any oxide, or other
28 insulator, covering the substrate 16. The substrate 16 may be,
29 for example, P-doped silicon and the dielectric layer 18 may be,
30 for example, a thermal oxide such as silicon dioxide.

31 The corona gun 26 is used to deposit a first polarity corona
32 charge (e.g., positive charge) on the measurement region 24 until
33 a desired electric field is established across the layer 18.
34 This electric field is chosen to be sufficient to move the mobile
35 charges in the layer 18 to the dielectric/substrate boundary

1 surface 22 during the temperature stress described below. This
2 field may be, for example, 2E6 volts/cm. The Kelvin probe 28 is
3 used to establish the electric field across the layer 18 based
4 on V_s and the thickness of the layer 18. In the preferred
5 embodiment, the corona is deposited incrementally and V_s measured
6 until the desired electric field is established.

7 The wafer 12 is then heated by the chuck 12 to a temperature
8 (e.g., 200-300 degrees centigrade) for a period of time (e.g.,
9 2-3 minutes) sufficient to allow the mobile charges to move to
10 the boundary surface 22. The wafer 12 is then allowed to cool
11 to room temperature (e.g., 20-25 degrees centigrade).

12 The heating and cooling the wafer 12 in the presence of
13 corona charge on the surface 20 is referred to herein as a corona
14 bias temperature stress cycle.

15 It is possible that movement of mobile charges during the
16 first corona bias temperature stress cycle will be sufficient to
17 reduce the electric field across the layer 18 to a value (e.g.,
18 less than 1.5E6 volts/cm) insufficient to move all of the mobile
19 charges in the layer 18 to the dielectric/substrate boundary
20 surface 22. If this is the case, additional corona of the first
21 corona polarity is applied to reestablish the desired electric
22 field across the layer 18 and another corona bias temperature
23 stress cycle applied. This is repeated until the electric field
24 across the layer 18, as determined by the Kelvin probe 28,
25 remains sufficient to have moved all of the mobile charges in the
26 layer 18 to the dielectric/substrate boundary surface 22 (e.g.,
27 greater than 1.5E6 volts/cm).

28 After the electric field remains sufficient to have moved
29 all of the mobile charges to the boundary surface 22, the corona
30 gun 26 is used to deposit corona of a second polarity (e.g.,
31 negative) on the measurement region 24 as a prelude to another
32 corona bias temperature stress cycle. The desired second
33 polarity corona charge electric field is chosen to be sufficient
34 to move the mobile charges in the layer 18 to the air/dielectric
35 boundary surface 20. This field may be, for example, -0.2E6

1 volts/cm. The wafer 12 is heated to, for example, 200-300
2 degrees centigrade for about a minute. The Kelvin probe 28 is
3 used to measure V_s after the corona is deposited and again at the
4 completion of the corona bias temperature stress cycle. The
5 voltage drop ΔV_s between the last corona deposit and the
6 completion of the corona bias temperature stress cycle is
7 determined.

8 It is possible that movement of mobile charges during the
9 first second polarity corona bias temperature stress cycle will
10 be sufficient to reduce the electric field across the layer 18
11 to a value (e.g., more positive than -0.1E6 volts/cm)
12 insufficient to move all of the mobile charges in the layer 18
13 to the air/dielectric boundary surface 20. If this is the case,
14 additional second polarity corona charge (e.g., negative) is
15 applied to reestablish the desired electric field across the
16 layer 18 and another corona bias temperature stress cycle
17 applied. The voltage drop ΔV_s is again determined. This is
18 repeated until the electric field across the layer 18, as
19 determined by the Kelvin probe 28, remains sufficient to move all
20 of the mobile charges in the layer 18 to the boundary surface 20
21 (e.g., more positive than -0.1E6 volts/cm).

22 If it is assumed the change in the surface potential ΔV_s is
23 just a result of the movement of mobile ion charges, ΔV_s can be
24 used to determine Q_{Mobile} from $1/q$ times C_{ox} times the sum of the
25 ΔV_s values, where q is the 1.6E-19 coulombs/unit charge and C_{ox}
26 is the capacitance per unit area of the dielectric (e.g., 3.45E-8
27 farads/cm² for 1,000 Å thick silicon dioxide). However, this
28 assumption severely limits the accuracy and usefulness of this
29 method of determining Q_{Mobile} .

30 Ideally, ΔV_s can be completely attributed to a momentary
31 ionic current across the dielectric. However, there will also
32 be some degree of leakage current (aggravated by the elevated
33 temperature used for the corona bias temperature stress cycle)
34 across the dielectric that will add to the apparent value of this
35 ionic current. While the wafer is at elevated temperatures

1 during a corona bias temperature stress cycle, the integral over
2 time of the leakage current will produce a voltage drop $\Delta V_{\text{Leakage}}$
3 which will additively contribute to the measured ΔV_s .

4 Also, ΔV_s is affected by any change in dipoles on the
5 surface of the dielectric. Dipoles will normally exist on the
6 dielectric surface, due to adsorbed molecules from the room
7 ambient. In general, such gaseous adsorption is favored at a
8 solid-gas interface, due to accompanying losses in surface free
9 energy as well as decreases in entropy. There are basically two
10 types of adsorption, chemical adsorption (chemisorption) and
11 physical adsorption. In chemisorption, often, the first
12 monolayer of gaseous molecules on a solid surface will have
13 tended to form chemical bonds, in order to satisfy unsaturated
14 surface bonds. In physical adsorption, multiple layers of
15 gaseous molecules can build up on a surface due to Van der Waals
16 forces. Any charge transfer that takes place during such gaseous
17 adsorption can lead to surface potentials, which can be
18 electrically likened to a battery sitting on the dielectric
19 surface. Any changes in this surface dipole potential ΔV_{Dipole}
20 during a corona bias temperature stress cycle can cause an
21 additive error in ΔV_s .

22 Additionally, as corona charge is applied to the dielectric,
23 the electric field lines from the corona charge will tend to
24 penetrate into the substrate 16. This field penetration into the
25 silicon will lead to changes in the silicon surface potential V_{Si}
26 resulting in "band-bending" error. The least worrisome case for
27 the changes in V_{Si} is when the silicon is in a state of being
28 accumulated (e.g., negative corona over a P-type silicon
29 surface). Here, the changes in V_{Si} may only be on the order of
30 tens of millivolts. The worst case for these V_{Si} changes is when
31 the silicon is in a state of depletion (and not yet inverted).
32 Here, the changes in V_{Si} , ΔV_{Si} may be on the order of hundreds of
33 millivolts.

34 These changes in V_{Si} become more of a source of error when
35 the oxide is very thin (e.g., less than 500 Å). For such thin

1 oxides, a given increment in corona charge or a given change in
2 corona bias temperature stress induced oxide charge (not Q_{Mobile})
3 might cause ΔV_{Si} to actually be greater than ΔV_s .

4 The present invention includes steps for correcting the
5 value of ΔV_s (and therefore Q_{Mobile}) for the effects of ΔV_{Dipole} , ΔV_{Si}
6 and $\Delta V_{Leakage}$.

7 As a correction for ΔV_{Dipole} , each of the successive second
8 polarity corona bias temperature stress cycles are chosen to be
9 of substantially equal time. This results in ΔV_{Dipole} being
10 minimized and thus less potential error in Q_{Mobile} . This is
11 because V_{Dipole} tends to recover to a prior equilibrium value over
12 a time span (e.g., 1-2 hours).

13 As another correction for ΔV_{Dipole} , a V_{Dipole} monitoring site is
14 created by depositing second polarity (e.g., negative) corona
15 charge with the corona gun 26 onto the measurement region 25
16 before a first polarity corona bias temperature stress cycle is
17 run on the measurement region 24. The second polarity corona
18 charge is applied until a desired electric field (e.g., 0.2E6
19 volts/cm) is established across the layer 18 at the region 25.
20 After completion of the first polarity corona bias temperature
21 stress cycle(s) at the region 24, the electric field across the
22 layer 18 at the region 25 is reduced to a value substantially
23 weaker (e.g., -0.05E6 to -0.1E6 volts/cm) than the desired value
24 for second polarity corona bias temperature stress cycles at the
25 region 24 by application of first polarity corona charge with the
26 corona gun 26. The Kelvin probe 28 is used to measure V_{S2} at the
27 region 25 before and after each second polarity corona bias
28 temperature stress cycle at the region 24. The value(s) of ΔV_s
29 is then corrected by subtracting the change in V_{S2} from each ΔV_s
30 with the controller 34, resulting in a corrected Q_{Mobile} .

31 This is because the contribution of ΔV_{Dipole} tends to be
32 independent of the electric field across the oxide. The
33 monitoring site at the region 25 will have the mobile ions
34 continuously at the surface 10 (i.e., no push-down field was
35 applied) and the reduced field will minimize leakage current,

1 therefore, the voltage drop ΔV_{S2} for each corona bias temperature
2 stress cycle corresponds to ΔV_{dipole} . It is noted that since a low
3 electric field is used to measure ΔV_{S2} at the V_{dipole} monitoring
4 site, ΔV_{Si} may not be constant. Therefore, further improvement
5 of the estimate of ΔV_{dipole} can be made by using the ΔV_{Si} correction
6 technique described below to ΔV_{S2} at the V_{dipole} monitoring site.

7 As a correction for ΔV_{Si} , the SPV tool 70 is used to make an
8 SPV measurement before and after each second polarity corona bias
9 temperature stress cycle. The difference between each pair of
10 SPVs is used as an estimate of ΔV_{Si} which is then subtracted from
11 ΔV_S by the controller 34 to provide a corrected value for Q_{Mobile} .

12 The light intensity of the SPV tool 70 must be sufficient
13 for creating a concentration of excess light induced carriers
14 that is comparable to or greater than the doping concentration
15 of the wafer (e.g., $1E15$ carriers/cm 3). The excess carriers
16 (electrons and holes) will separate in the silicon surface field,
17 due to V_{Si} , and then set up an opposing field that will tend to
18 reduce V_{Si} toward zero. Therefore, the magnitude of the SPV
19 (actually, the change in V_{Si}) will tend to be a significant
20 fraction of V_{Si} . For silicon, in the depletion regime, the SPV
21 can be as much as 80% of V_{Si} . For the accumulation regime, the
22 SPV will tend to be about 30% of V_{Si} .

23 For a given value of SPV and a reasonably estimated value
24 of excess optically induced carrier generation, Δn , there
25 will be an approximate corresponding value of V_{Si} that can be
26 calculated from a theoretical model, such as that of E.O.
27 Johnson, Phys. Rev., Vol. 111, No. 1. The first order effect in
28 the Johnson model is that the magnitude of SPV tends to approach
29 V_{Si} as Δn becomes comparable to and larger than the silicon
30 doping concentration. It is noted that Δn can also be
31 estimated from Johnson, based on a SPV measurement in strong
32 accumulation and in strong inversion.

33 To provide a correction for $\Delta V_{\text{leakage}}$, second polarity corona
34 bias temperature stress cycles are applied to the wafer 14 at the
35 region 24, until the corresponding values for ΔV_S approach a

1 terminal value, $\Delta V_{\text{terminal}}$. Estimates for the terminal ΔV_{dipole} and
2 the terminal ΔV_{si} (e.g., from the above described methods) are
3 subtracted from $\Delta V_{\text{terminal}}$ to provide an estimate for $\Delta V_{\text{leakage}}$. The
4 value(s) of ΔV_s is then corrected by subtracting $\Delta V_{\text{leakage}}$ from each
5 ΔV_s by the controller 34 and a corrected Q_{Mobile} is provided.

6 This is because after the first one or two second polarity
7 corona bias temperature stress cycles, all the second polarity
8 mobile ions will have moved to the surface 20 (particularly for
9 sodium ions). The ideal terminal value of ΔV_s would be
10 essentially zero. However, due to the aforementioned error
11 factors, $\Delta V_{\text{terminal}}$ will usually be a non-zero value that will
12 correspond to the sum of the terminal values of $\Delta V_{\text{leakage}}$, ΔV_{dipole}
13 and ΔV_{si} . Prior to attaining the $\Delta V_{\text{terminal}}$ condition, the
14 successive values of ΔV_s will equal the sum of the corresponding
15 oxide voltage drop due to mobile ions, ΔV_{ox} , along with the
16 corresponding $\Delta V_{\text{leakage}}$ and ΔV_{dipole} . Fortunately however, $\Delta V_{\text{leakage}}$
17 can usually be assumed to be constant for each successive second
18 polarity corona bias temperature stress cycle as the bias field
19 is essentially the same for each cycle (i.e., the terminal value
20 of $\Delta V_{\text{leakage}}$ can be used for all values of $\Delta V_{\text{leakage}}$).

21 To provide another correction for $\Delta V_{\text{leakage}}$, before each second
22 polarity corona bias temperature stress cycle, the amount of
23 corona charge necessary to bias the portion of the substrate 16
24 below the region 24 from midband condition to the desired second
25 polarity corona charge electric field (pull-up condition) is
26 determined from Q_c . After each second polarity corona bias
27 temperature stress, the amount of corona charge necessary to bias
28 the portion of the substrate 16 below the region 24 back to
29 midband condition is determined from Q_c . The difference between
30 these two amounts of charge, Q_{Restore} , provides a measure of $\Delta V_{\text{leakage}}$
31 where $\Delta V_{\text{leakage}}$ is equal to Q_{Restore} divided by C_{ox} . The value(s) of
32 ΔV_s is then corrected by subtracting $\Delta V_{\text{leakage}}$ from each ΔV_s with
33 the controller 34 and a corrected Q_{Mobile} is provided.

34 The midband condition for the substrate 16 may be determined
35 with the SPV tool 70. For example, for 10-20 ohm-cm silicon, the

1 midband SPV would be -0.3 volts. As corona charge is
2 incrementally deposited by the corona gun 26, the SPV tool 70 is
3 used to identify the midband condition.

4 This correction comes about because changes in dielectric
5 surface dipole potentials, after a corona bias temperature stress
6 cycle, tend to be accompanied by no net change in net oxide
7 surface charge. Consequently, there is no accompanying change
8 in silicon imaging charge, assuming no net change in oxide/Si
9 interface states occupancy after a corona bias temperature stress
10 cycle. In contrast, for leakage, there is a net change in oxide
11 surface charge and silicon image charge that can be accounted for
12 with Q_{Restore} .

13 The above methods for determining and correcting Q_{Mobile} can
14 also be advantageously combined. Corrections for $\Delta V_{\text{Leakage}}$, ΔV_{Dipole}
15 and ΔV_{Si} determined from the above methods can, for example, be
16 each used in any desired combination and, in the case of multiple
17 corrections for the same error mechanism, averaged or otherwise
18 weighted. In addition the values for $\Delta V_{\text{Leakage}}$, ΔV_{Dipole} and ΔV_{Si} can
19 be fitted to theoretical models, and corrections therefrom
20 applied to Q_{Mobile} .

21 It should be evident that this disclosure is by way of
22 example and that various changes may be made by adding, modifying
23 or eliminating details without departing from the fair scope of
24 the teaching contained in this disclosure. The invention is
25 therefore not limited to particular details of this disclosure
26 except to the extent that the following claims are necessarily
27 so limited.